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16. Abstract

Time dependent calculations of minor species distributions require as input the solar radiation field as a function of altitude and solar zenith angle. An isotropic spherical model of the radiation field has been developed to determine the solar radiation field in twilight. Comparison of the spherical model with a plane parallel model of the multiple scattering of radiation at twilight shows that: (1) for solar zenith angles less than $95°$, plane parallel solutions are suitable if the initial deposition of solar energy is calculated for a spherical atmosphere; (2) for solar zenith angles greater than $95°$, the plane parallel radiation field is several orders of magnitude smaller than that calculated with the spherical model; (3) at altitudes above 40 km, the spherical model predicts 10 - 20 % less radiation than the radiation field calculated with the plane parallel model.

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THE SOLAR RADIATION FIELD AT TWILIGHT

BELOW 100 KM: A SPHERICAL MODEL

by

Donald E. Anderson, Jr.
E. O. Hulburt Center for Space Research
Naval Research Laboratory
Washington, DC 20375

Abstract

   Time dependent calculations of minor species distributions require
as input the solar radiation field as a function of altitude and solar
zenith angle. An isotropic spherical model of the radiation field has
been developed to determine the solar radiation field in twilight.
Comparison of the spherical model with a plane parallel model of the
multiple scattering of radiation at twilight shows that: (1) for solar
zenith angles less than $95°$, plane parallel solutions are suitable if the
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field is several orders of magnitude smaller than that calculated with
the spherical model; (3) at altitudes above 40 km, the spherical model
predicts 10 - 20 % less radiation than the radiation field calculated
with the plane parallel model.

CONTENTS

I. Introduction

Time dependent calculations of minor species distributions require as input the solar radiation field as a function of altitude z and solar zenith angle θ_0. There has been some concern that results from plane parallel models may be incorrect at twilight. In the present study, an isotropic spherical model of the radiation field has been developed to address the twilight problem. The model does not include refraction effects, ground albedo, or aerosols, but does include molecular oxygen (O_2) and ozone (O_3) absorption, and multiple scattering in an inhomogeneous, spherical atmosphere. Ground albedo is relatively unimportant in twilight; refraction effects may be neglected except when making comparison to high resolution measurements; and the presence of aerosols slightly enhance the degree of multiple scattering at all wavelengths. These effects may be included at a later time but the basic results described here will not be affected.

II. The Models

The model atmosphere employed is the U.S. Standard Atmosphere (1976) with the O_3 profile from Nicolet (1978). The O_3 cross section between 200 and 800 nm is also from Nicolet (1978), as is the O_2 absorption cross section. The model atmosphere is shown in Figure 1 and the O_3 and O_2 cross sections in Figure 2.

The spherical radiative transfer model is patterned after the model developed by Anderson and Hord (1977) for calculation of resonance scattering by atomic hydrogen of the solar Lyman-alpha flux incident on planetary thermospheres and exospheres. The basic physical model for Rayleigh and Mie scattering is described for the plane parallel case by

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Anderson and **Meier** (1979) and **Meier** et al., (1982). Detailed numerical results for the wavelength region **200-800 nm** in the troposphere and stratosphere are described by **Nicolet** et al., (1982).

Briefly, both the plane parallel and spherical theory used in this study solve the integral equation of radiative transfer for the flux into a volume element F. F is normalized to the solar flux at the top of the atmosphere F_∞, where F_∞ is in units photons $cm^{-2}s^{-1}nm^{-1}$. The plane parallel model assumes azimuthal symmetry and utilizes **Chandrasekhar's** (1960) E functions to reduce the problem to one dimension: namely F as function of vertical optical depth τ, or altitude. In the spherical code, azimuthal symmetry is assumed, but F is now an interlocking function of τ and Θ_0. Thus, on multiple scattering, photons are allowed to migrate in both τ and Θ_0. It will be shown below that the effects of this coupling can be very large in twilight.

III. Results

A. Calculation of F_0

When plane parallel models are employed to calculate $F(\tau, \Theta_0)$, the attenuated direct flux $F_0(\tau, \Theta_0)$ is usually given by

$$F_0(\tau, \Theta_0) = exp[-(\tau + \tau_p) \sec\Theta_0] \qquad (1)$$

τ is related in a straightforward way to z noting that

$$\tau = \sigma_R \int N(z)dz \qquad (2)$$

where σ_R is the cross section for **Rayleigh** scattering, and N is the neutral atmosphere density at altitude z in the atmosphere. An absorption which removes a photon from further scattering is designated a pure absorption, and the pure absorption optical depth is

$$\tau_p = \int [\sigma_{O3}N_{O3}(z) + \sigma_{O2}N_{O2}(z)]dz \qquad (3)$$

where the u's are the pure absorption cross sections. If the pure

absorber is homogeneously mixed with the scatters, then Chapman functions

(Smith and Smith, 1972) may be used in place of sec θ_0 in (1) to account for

effects on F_0 of sphericity. Since O_3 is not homogeneously mixed neither

Chapman functions, nor sec θ_0 is appropriate. Instead, the true slant

optical depth must be calculated taking into account the inhomogenities due

to ozone. A comparison of (1) with the correct F_0 is shown in Figure 3

at θ_0 = 80, 86, and 88^0, for A = 325 nm, r_p = 0.14 and λ = 325 nm,

τ_p = 0, respectively. Clearly, below 50 km, spherical effects are

important for θ_0 > 80^0. No comparisons are made for $\theta_0 \geq 90$,

since the plane parallel F_0 is not defined. In Figure 4, F_0 is shown

for λ = 325 nm and θ_0 from 0^0 to 98^0. The wavelength A = 325 nm

is chosen throughout for illustrative purposes, since both pure absorption

and multiple scattering effects are important. However, the model does

cover the entire range 200 - 800 nm.

B. Calculation of F

    Values of F at λ = 325 nm are shown in Figure 5 for θ_0 = 60^0 to

104^0. The dashed curves are the values of F calculated with the correct

spherical F_0, but the multiple scattering is assumed to take place in a

plane parallel atmosphere. It is clear from Figure 5 that for θ_0 < 92^0

the plane parallel solution with a spherical F_0 is adequate to describe

the multiple scattering. However, for θ_0 > 96^0 the plane parallel

solutions are orders of magnitude lower than the spherical solutions and

are off scale.

    Another result, not apparent on the log plot in Figure 5, is that

above 40 km, F (spherical) falls about 10 to 20% below F (plane parallel)

at all θ_0. This result has been noted before (Strickland and Anderson,

1973) and occurs because a photon emitted at a given altitude in a spherical atmosphere has a greater probability of escape from the medium than in a plane parallel atmosphere. As $z \to \infty$ the escape probability approaches 0.5 in a plane parallel medium, and 1.0 in a spherical medium.

As an example of the wavelength dependence, Figures 6 and 7 show $F(\Theta_0)$ for λ = 250 and 450 nm, respectively. At short wavelengths (λ < 325 nm) ozone absorbs much of the radiation so that F is low, and is essentially zero below the ozone maximum. As λ increases beyond 350 nm F gradually decreases in proportion to the Rayleigh optical depth, and thus the multiple scattering decreases.

IV. Discussion

The purpose of this research effort was: (1) to develop a spherical model of the multiple scattering of solar radiation in the twilight atmosphere; and (2) to establish a range of validity for the use of plane parallel models in twilight. The initial model has been developed. A more sophisticated model may be developed in the future which includes such effects as refraction of sunlight, anistropic scattering by aerosols, ground albedo, and clouds. But the result of comparison with the present model and a plane parallel model suggests that for $\Theta_0 < 95^0$, the plane parallel solution is sufficient, if the proper F_0 is used. This conclusion is stated with the caveat that the spherical solutions are 10-20% lower than the plane parallel solutions at all Θ_0 for z > 40 km.

For $\Theta_0 > 95^0$ plane parallel solutions are not satisfactory, and the future improvement of the present model depends to some extent on whether or not the enormous differences in F between the two models have any effect on the photochemistry in the atmosphere below 100 km.

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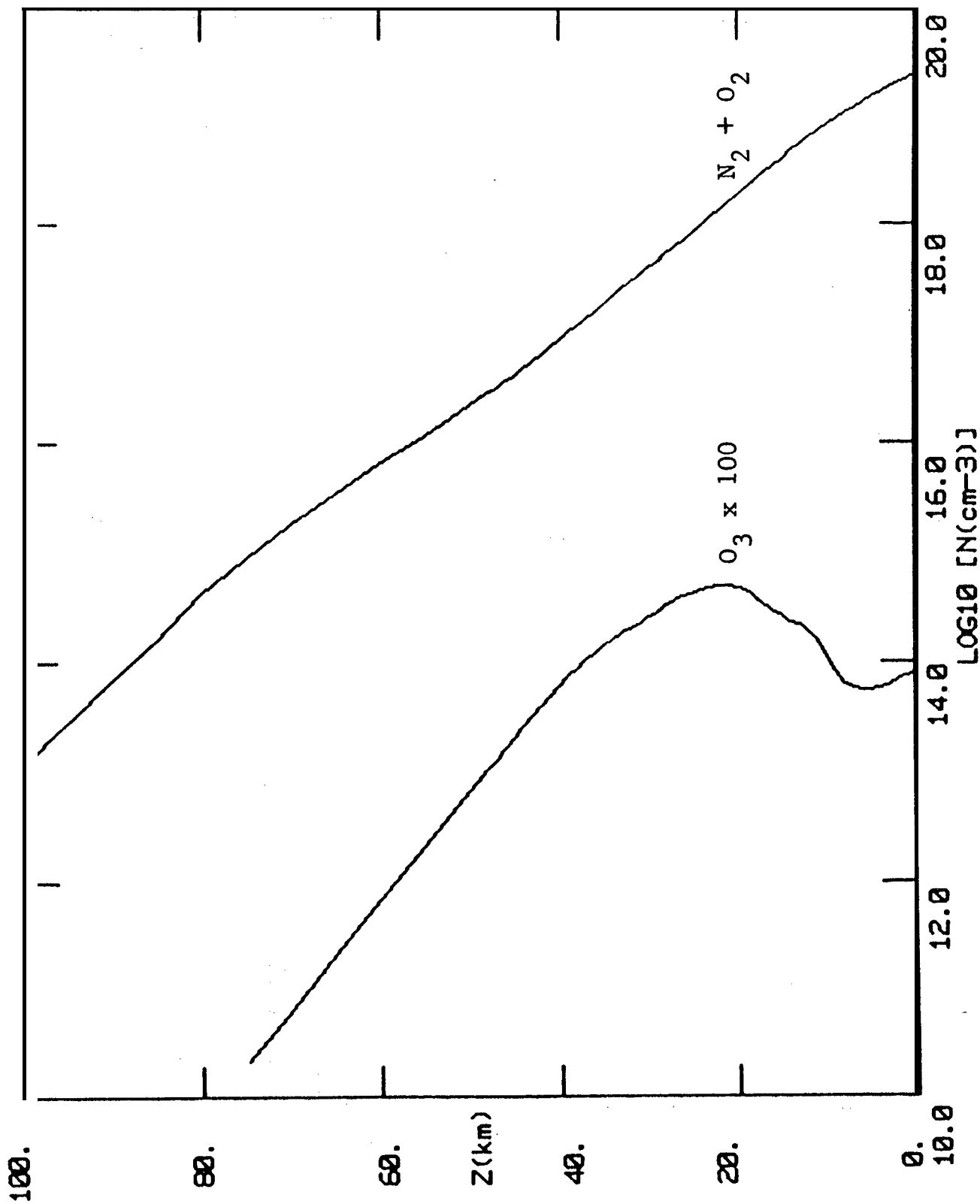
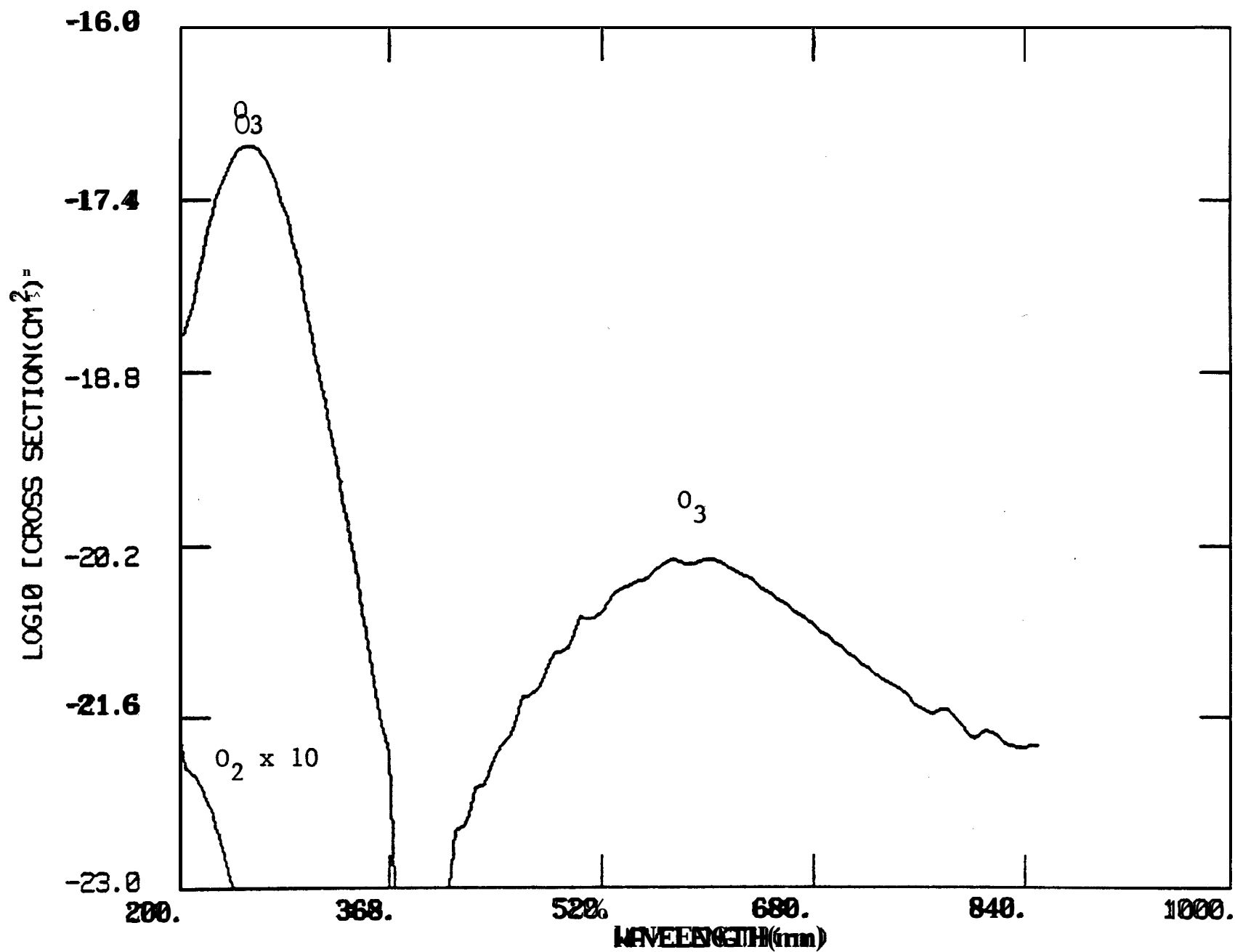Figure 1. Neutral Atmosphere Density Distribution. Ozone is scaled
by a factor of 100.

Figure **2.** O$_2$ and O$_3$ pure absorption cross sections. O$_2$ cross section is scaled upward by a factor of **10.**
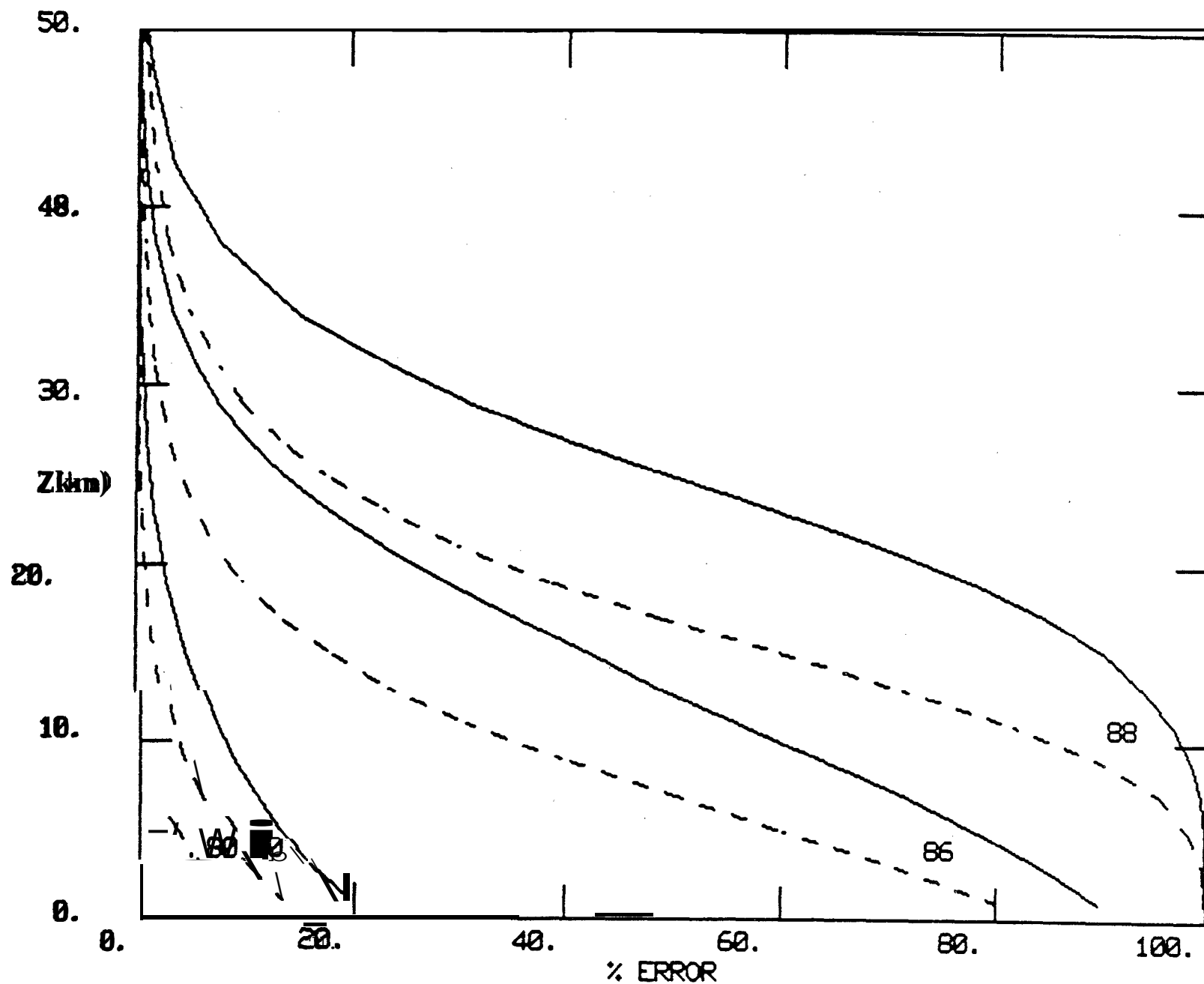
Figure **3.** Percent error in plane parallel F_o when compared to spherical F_o at $\lambda = 325$ nm and θ_o as indicated. Dashed and solid curves are for $\tau_p = 0$ and **0.14**, respectively.
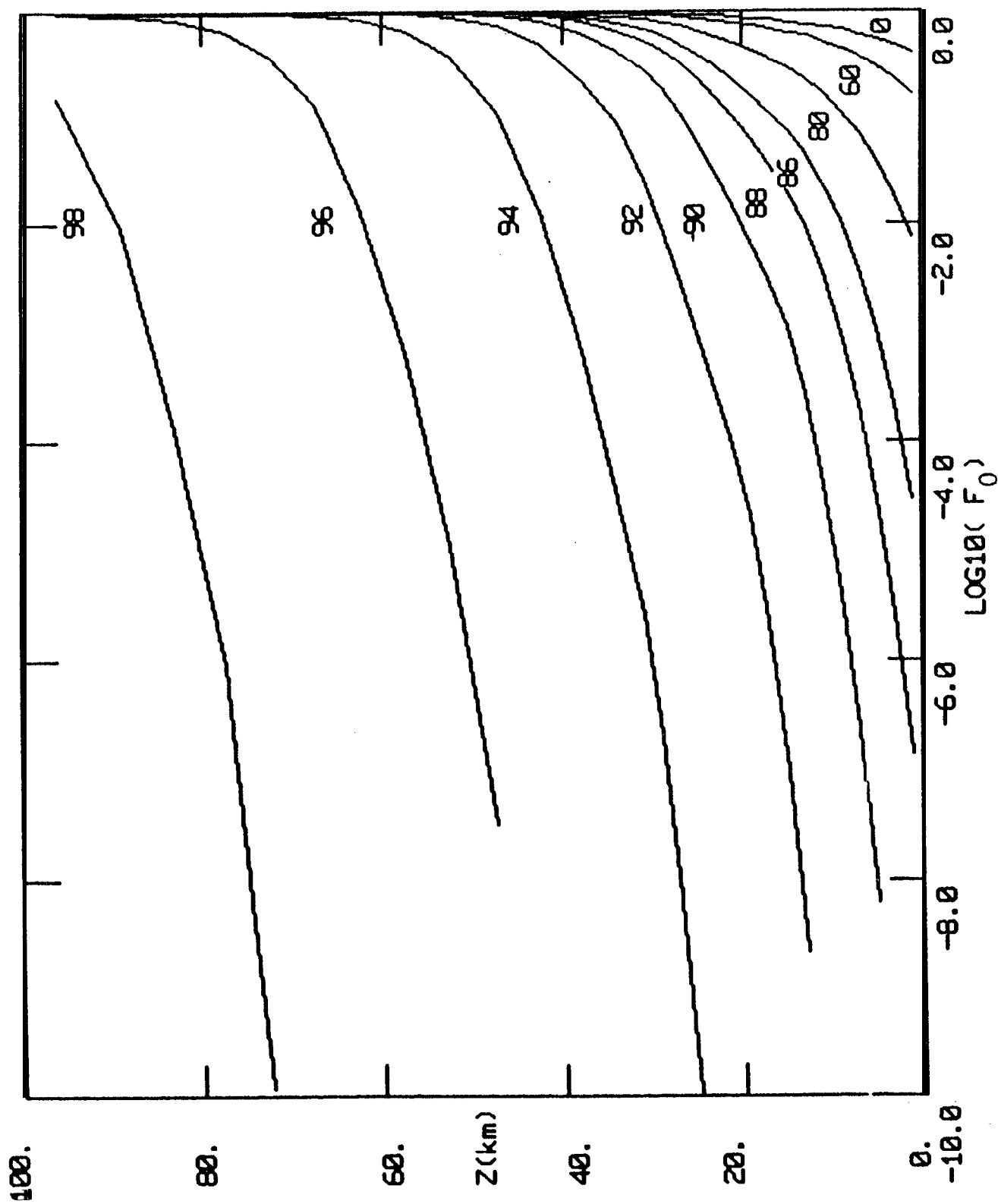
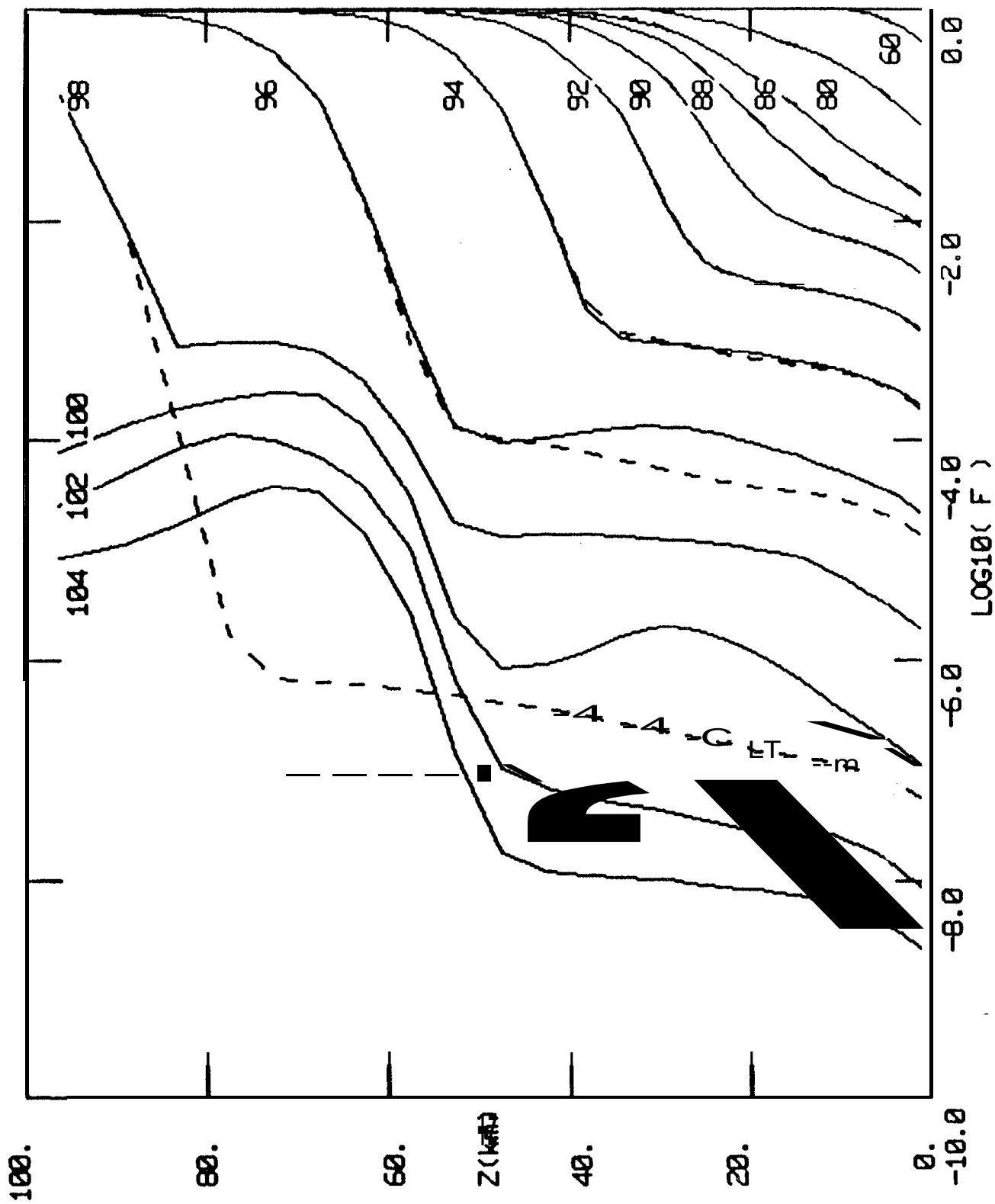Figure 4. Spherical F_O at $\lambda = 325$ nm and, θ_O as indicated.

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Figure 5. F as a function of Θ_o at $\lambda = 325$ nm. Solid curves are spherical solutions, and dashed curves are plane parallel solutions. Θ_o as indicated.
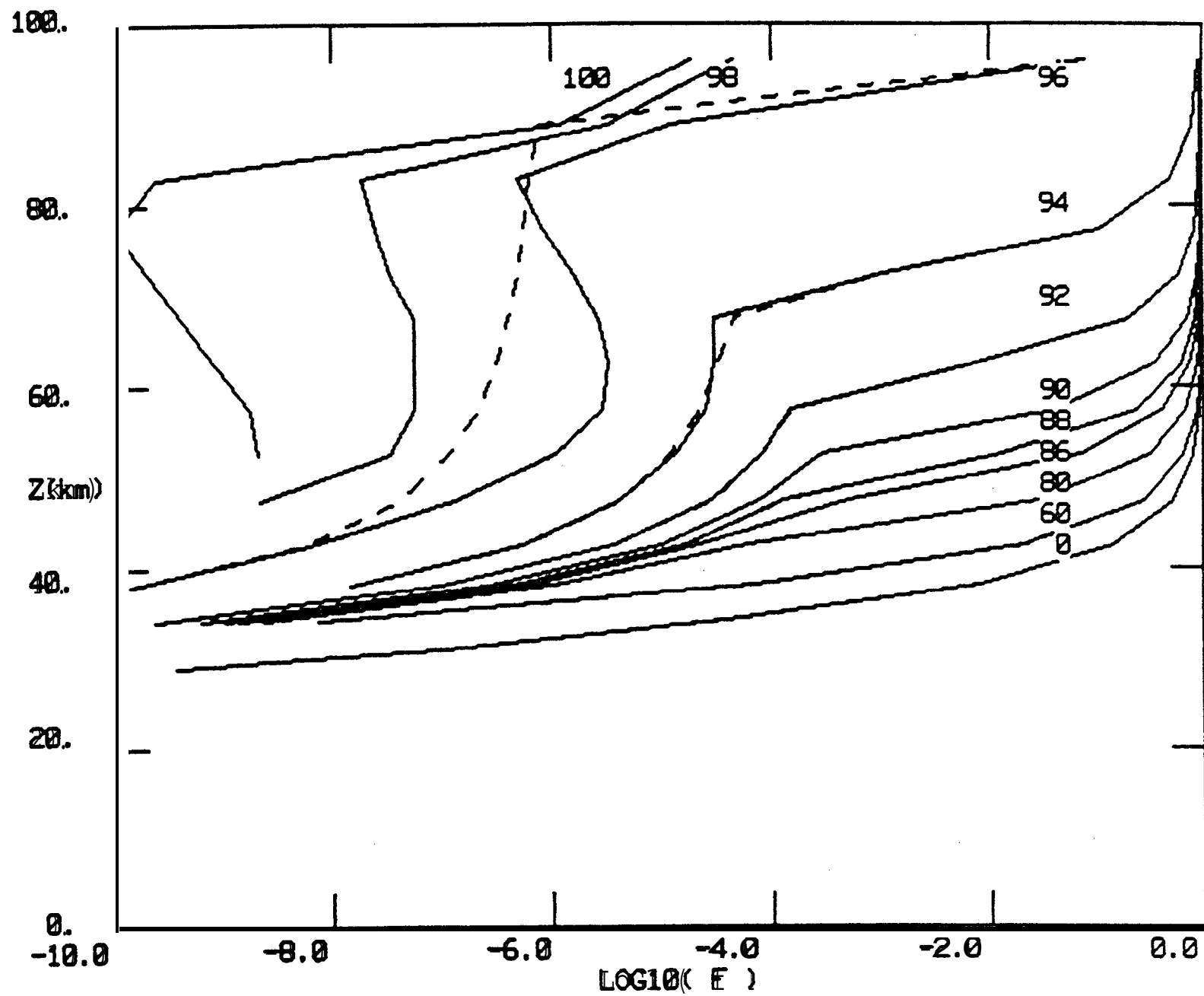
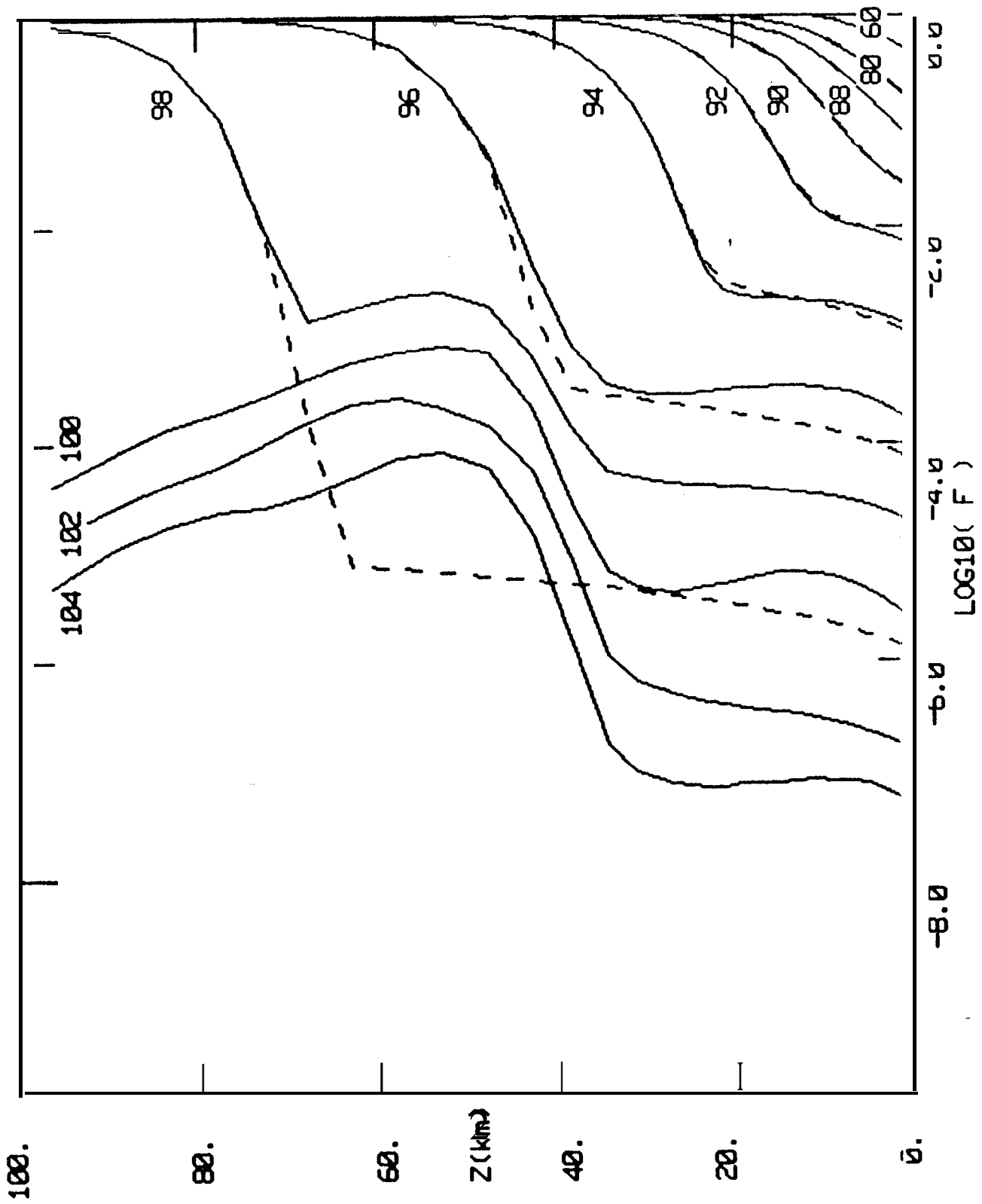Figure **6.** F as a function of θ_0 at $\lambda = 250$ nm. See Figure 5 caption.

Figure 7. F as a function of Θ_0 at λ = 450 nm. See Figure 5 caption.

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